Discovery of a planetary-sized object in the scattered Kuiper belt

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ABSTRACT

We present the discovery and initial physical and dynamical characterization of the object 2003 UB313. The object is sufficiently bright that for all reasonable values of the albedo it is certain to be larger than Pluto. Pre-discovery observations back to 1989 are used to obtain an orbit with extremely small errors. The object is currently at aphelion in what appears to be a typical orbit for a scattered Kuiper belt object except that it is inclined by about 44 degrees from the ecliptic. The presence of such a large object at this extreme inclination suggests that high inclination Kuiper belt objects formed preferentially closer to the sun. Observations from Gemini Observatory show that the infrared spectrum is, like that of Pluto, dominated by the presence of frozen methane, though visible photometry shows that the object is almost neutral in color compared to Pluto's extremely red color. 2003 UB313 is likely to undergo substantial seasonal change over the large range of heliocentric distances that it travels; Pluto at its current distance is likely to prove a useful analog for better understanding the range of seasonal changes on this body.

Subject headings: comets: general – infrared: solar system – minor planets

1. Introduction

Since the discovery of the first small objects beyond Neptune (Jewitt & Luu 1993) astronomers have speculated about the existence of objects larger than Pluto in the Kuiper

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belt. Extrapolation of the size distribution of smaller Kuiper belt objects (KBOs) has sometimes been used to attempt to estimate the numbers of such larger objects (i.e. Bernstein et al. 2004), but such estimates have proven inconclusive. One of the goals of our ongoing survey for bright KBOs (Trujillo & Brown 2003) is to find the rare objects at the bright end of the Kuiper belt magnitude distribution. Such bright objects are invaluable as targets for detailed physical study (Marchi et al. 2003; Jewitt & Luu 2004; de Bergh et al. 2005; Trujillo et al. 2005) in addition to being potential beacons of previously unknown populations (Brown et al. 2004; Kenyon & Bromley 2004; Morbidelli & Levison 2004).

The newly discovered KBO 2003 UB313 is currently the fourth brightest object known in the Kuiper belt (after Pluto, 2003 FY9, and 2003 EL61) and is currently the most distant object ever seen in orbit around the sun. As an object notable for its brightness, distance, and size, 2003 UB313 is certain to be the object of intensive study. We present here details on its discovery, preliminary observations about its surface characteristics, and some suggestions about physical processes operating on this object.

2. Discovery

2003 UB313 was discovered in data from 21 October 2003 obtained from our ongoing survey at the 48-inch Samuel Oschin telescope at Palomar Observatory. At the time of discovery the object was moving 1.42 arcseconds per hour, slower than the cut-off in our main survey (Trujillo & Brown 2003). Our survey obtains three images over a 3 hour period. With typical image quality of from 2 to 3 arcseconds, slower motions are clearly detectable, but we installed a 1.5 arcsecond per hour lower limit to our analysis to cut down the copious false positives at the slow end. The discovery of Sedna (Brown et al. 2004), with a motion of 1.75 arcseconds per hour, however, suggested a need to efficiently search for distant objects which would be moving at lower rates.

We have now reanalyzed all survey data with a second ("slow") detection scheme in addition to the standard ("fast") scheme. This slow scheme searches for motions between 1 and 2 arcseconds per hour between the first and third image of a triplet. When a potential object is found it checks for consistency using the second image, but motion need not be detected between either the first and second or second and third images. Finally, to remove the large number of false positives generated by stationary stars, all potential detections which are within 2 arcseconds of a catalogued USNO star are removed without examination. The slow scheme generates 10 to 20 times more false positives than the fast scheme, leading to approximately 1200 candidates every month. These candidates are examined by eye and

are generally quickly rejected. On occasion we also make use of the Skymorph data base[1] to determine that a potentially moving candidate is, in fact, a stationary star. In the two years worth of slow data examined to date we have found only two real objects: Sedna (previously also found in the fast scheme) and 2003 UB313.

The extreme brightness and slow motion of 2003 UB313 made it easy to identify it as a transient in archival data. The object was identified in multiple images from the Skymorph data base and eventually found in a 1989 plate from the UK Schmidt telescope at Siding Springs Observatory. From this 16-year orbital arc the derived barycentric orbit using the method of Bernstein & Khushalani (2000) gives a semi-major axis, eccentricity, and inclination of $a = 67.89 \pm 0.01$, $e = 0.4378 \pm 0.0001$, and $i = 43.993 \pm 0.001$, respectively. 2003 UB is currently near aphelion at 97.50 ± 0.01 AU from the sun and will not reach perihelion at 38.2 AU until the year 2257.

Based on the semi-major axis and eccentricity, 2003 UB313 would be classified as a typical member of the scattered Kuiper belt (Morbidelli & Brown 2005). The inclination of 44 degrees is extreme for the scattered belt, however. Only one other otherwise unremarkable scattered object (2004 DG77) has a confirmed orbit with an inclination as high. While initial models of the scattered Kuiper belt (Duncan & Levison 1997) were incapable of populating high inclination regions, recent work (Gomes et al. 2005) suggests that a combination of gravitational scattering, mean-motion resonant interaction, planetary migration, and the Kozai mechanism may be able to place objects into orbits such as these. Additional simulations show that objects that are initially in the inner part of the pre-migration disk (at distances of ~ 20 AU) are scattered into orbits with higher inclinations than those further out (Gomes 2003). We expect that, on average, these inner regions will lead to the formation of larger objects owing to both higher nebular densities and shorter accretion time scales. We might therefore expect to find other large objects at high inclination in the scattered Kuiper belt. Indeed, the other two recently announced scattered KBOs from our survey, 2005 FY9 and 2003 El61, both have inclinations near 30 degrees and approach the size of Pluto.

3. Spectrum

Visible photometry of 2003 UB313 was obtained on 5, 6, and 7 January 2005 using the 1.3-meter SMARTS telescope. Data were obtained and reduced in an identical manner to that described in Rabinowitz et al. (2005). Infrared photometry was obtained on 25 and 26 January from the Gemini North Observatory. No evidence for any photometric variation

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[1]http://skys.gsfc.nasa.gov/skymorph/skymorph.html

was seen over the short time scale of observation. Table 2 gives photometric and relative reflectance values from the visible to the near infrared. No attempt is made to correct for solar phase effects, which are of order 0.01 magnitudes at Pluto for a 0.5 degree phase (Tholen & Buie 1997). The relative brightness of 2003 UB313 is highest in the R and I filters. We find an absolute magnitude of $H_r = -1.48$, which corresponds to a diameter of $2250\rho_r^{-1/2}$ km, where ρ_r is the R albedo. Even if the surface albedo is an unreasonably high 100% at these wavelengths the object has a diameter approximately that of Pluto.

Medium resolution near-infrared spectra were obtained on the nights of 25-27 January UT with the Near Infrared Imager and Spectrograph (NIRI, Hodapp et al. 2003) instrument on the Gemini North telescope. The J, H and K bands were measured using 3 separate grating settings and on-source times of one, one, and two hours, respectively. Relative reflectance was computed by dividing the spectra by a solar analog G2V star at a similar airmass to 2003 UB313. Each spectra was pair subtracted to remove detector bias, then flattened and rectified. Bad pixels and cosmic rays were masked out in each spectrum prior to extraction. Extracted spectra were rebinned to a common wavelength scale with regions affected by bright OH lines masked out. Error bars were computed from the reproducibility of spectral data in each wavelength bin. Though 2003 UB313 is relatively bright, the signal-to-noise of the spectrum is only moderate owing to the fact that at the time of discovery the object was quickly setting in the evening sky. Figure 1 shows the relative reflectance of 2003 UB313, with the individual J, H, and K spectra scaled to match the near-infrared photometry and the relative near-infrared colors of Pluto. Because of uncertainties in spectral slope across the near-infrared, we do not regard the relative scaling between the three separate spectra to be reliable. The near-infrared spectrum is dominated by absorption from CH_4 and closely resembles that of Pluto. At the current signal-to-noise and systematic reproducibility level, no reliable detection is made of any other species on 2003 UB313, including, notably, the 2.15 μm line of N_2, the 1.58 μm line of CO, both detected on Pluto (Owen et al. 1993), and the 2.01 and 2.07 μm lines of CO_2 detected on Triton (Cruikshank et al. 1993). In many cases there are potentially detections of these lines, but most are in spectral regions contaminated by bright sky lines or variable sky absorptions and none should be believed without additional observation and confirmation.

One major difference between the spectrum of 2003 UB313 and that of Pluto is that the visible region of 2003 UB313 is considerably less red than that of Pluto. If red visible colors on icy bodies are interpreted as due to irradiated complex organics, the difference between Pluto and 2003 UB313 is surprising given the similarity of the methane spectra of the two bodies. A more subtle difference between the spectra is a slight shift of the positions of the methane absorption lines (Table 2). On Pluto methane is a minor component dissolved as a solid solution inside of N_2 ice. The isolation of the methane molecules leads to a slight but

measurable energy shift in the spectrum (Quirico & Schmitt 1997). The four best measured methane lines on 2003 UB313, in contrast, appear much closer to the positions measured in the laboratory for pure methane than they do for methane incorporated into N_2.

4. Discussion

2003 UB313 is the largest known object in orbit beyond Neptune, and, like the second largest object, Pluto, its spectrum is dominated by absorption due to methane. Methane ices subjected to ion and UV radiation irreversibly break down and reassemble into more complex hydrocarbons (Moore et al. 2003), leading eventually to the formation of dark red tholins (Khare et al. 1984). The continued presence of abundant methane on 2003 UB313 suggests the need, as has been suggested for Pluto (Spencer et al. 1997), for an interior source to replenish the methane. The presence of methane on 2003 UB313 as well as Pluto suggests that this process is ubiquitous in the outer solar system and that methane is not retained on smaller objects where escape rates are higher (Trafton et al. 1997).

The red colors and large spatial albedo variations of Pluto have been suggested to be due to distinct regions covered by these dark red tholins. At Pluto's current heliocentric distance, dark regions absorb enough sunlight to become too warm for methane condensation, while the bright regions serve as methane cold traps, thus reinforcing any albedo contrast in existence (Brown 2002). At the 97 AU distance of 2003 UB313, however, even dark regions will be sufficiently cold that as methane freezes out of the atmosphere or is replenished from the subsurface it will cover the entire body, lowering albedo contrasts and hiding the red tholins. This model leads to the prediction that 2003 UB313 will have significantly less albedo variation than Pluto and that its albedo will be as high or higher than Pluto.

The lower temperature of 2003 UB313 may also explain the difference in the state of the methane. Expected subsolar surface temperatures of a 70% albedo body at 97 AU are $\sim$30 K. At this temperature the vapor pressure over pure N_2 ice is 420 nbar, while the vapor pressure over pure methane ice is below a pbar (Spencer et al. 1997). Unlike Pluto's present state, methane on 2003 UB313 is currently essentially involatile and will not be mixed in the atmosphere with nitrogen. As 2003 UB313 moved towards aphelion over the past two centuries nitrogen and methane may have segregated, perhaps vertically. As 2003 UB313 moves back towards perihelion a more Pluto-like mixing may occur.

The discovery of 2003 UB313 provides a new lower temperature laboratory for the study of many of the processes discussed for Pluto, including atmospheric freeze out and escape, ice chemistry, nitrogen phase transitions, and volatile mixing and transport. The

temperature variation from perihelion of aphelion of 2003 UB313 is even more extreme than that on Pluto. Higher quality infrared spectra, which should be readily obtainable for this moderately bright object, will be a key component of future studies.

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Fig. 1.— Relative reflectance of 2003 UB313 (solid points with error bars) and absolute reflectance of Pluto (red line). The large points are the reflectance derived from BVRIJHK photometry. Every reliably identifiable feature in the 1 - 2.5 μm region of the spectrum of 2003 UB313 is due to absorption by solid methane. The absolute geometric albedo of 2003 UB313 is not yet known. The relative reflectance is scaled to match that of Pluto in the I band for comparison. The Pluto spectrum is a compilation from Trafton & Stern (1996), Grundy & Fink (1996), Rudy et al. (2003), and Douté et al. (1999).

Table 1: Photometry of 2003 UB313

filter	magnitude	relative reflectance
B	$19.54 \pm .01$	0.88
V	$18.83 \pm .02$	0.92
R	$18.38 \pm .02$	1.00
I	$18.05 \pm .02$	1.00
J	$17.82 \pm .02$	0.86
H	$18.11 \pm .03$	0.51
K	$18.51 \pm .05$	0.32

Table 2: Positions of methane lines

line identification	2003 UB31[a] (μm)	pure methane[b] (μm)	methane in nitrogen[b] (μm)
$\nu_2 + 2\nu_3 + \nu_4$	1.138	1.139	1.136
$2\nu_3 + \nu_4$	1.165	1.165	1.161
$2\nu_3$	1.670	1.670	1.666
$\nu_2 + \nu_3 + \nu_4$	1.723	1.725	1.720

[a]Wavelength uncertainties are approximately $\pm 0.002 \mu$m

[b]aboratory data from Quirico & Schmitt (1997)